# Response of a MEMS Microshutter Operating at 60 K to Ionizing Radiation

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*Abstract*—Total ionizing dose (TID) measurements at low temperature (60 K) of a Micro-Electro-Mechanical System (MEMS) Microshutter Array (MSA) indicate that exposing the MSA to ionizing radiation causes some of the shutters to stop operating properly. The number of non-functional shutters depends on the applied bias. With increasing dose, the number of micro-shutters that become non-functional increases.

*Index Terms*—Insulators, low temperature, micro-electro-mechanical system, total ionizing dose.

## I. INTRODUCTION

THE James Webb Space Telescope (JWST), the successor to the Hubble Space Telescope, is due to be launched in 2013 with the goal of searching the very distant Universe for stars that formed shortly after the Big Bang. Because this occurred so far back in time, the available light is strongly red-shifted, requiring the use of detectors sensitive to the infrared portion of the electromagnetic spectrum. HgCdTe infrared focal plane arrays, cooled to below 30 K to minimize noise, will be used to detect the faint signals.

One of the instruments on JWST is the Near Infrared Spectrometer (NIRSPEC) designed to measure the infrared spectra of up to 100 separate galaxies simultaneously. A key component in NIRSPEC is a Micro-Electromechanical System (MEMS), a two-dimensional micro-shutter array (MSA) developed by NASA/GSFC. The MSA is inserted in front of the detector and the optics forms an image of the galaxies on the MSA. Only those shutters on which galaxy images of interest are focused are opened to allow the light to reach the detector. Light from all other images not targeted for analysis are prevented from reaching the detector by the closed shutters.

JWST will be located at $L_2$, the Lagrangian point approximately $1\,500\,000$ km from the Earth in the opposite direction to the Sun. The radiation environment of concern at L2 consists primarily of energetic solar particles and cosmic rays that produce total ionizing dose (TID) effects. These effects may be quite severe because the MSA will be located outside the spacecraft with little shielding, resulting in a TID of approximately 200 krad(Si) over the life of the mission. Furthermore, all optical components in NIRSPEC, including the MSA, will be cooled to 30 K to minimize the amount of extraneous thermal radiation from reaching the detector and swamping the faint signals of interest. Low temperatures could exacerbate the effects of TID on the MSA.

Following exposure to ionizing radiation, MEMS of various types have exhibited performance degradation [1]–[6]. MEMS contain moving parts that are either controlled or sensed by changes in electric fields. Radiation degradation can be expected for those devices where there is an electric field applied across an insulating layer that is part of the sensing or controlling structure. Ionizing radiation passing through an insulating layer liberates charge (electrons and holes) and some of that charge may become trapped within that layer. Trapped charge will partially cancel any externally applied electric field and lead to changes in the operation of the MEMS. Based on the previously published reports, this appears to be a general principle for MEMS [1]–[6].

Knowledge of the above principle has raised concern at NASA that the MSA might also exhibit degraded performance because, i) each shutter flap is a multilayer structure consisting of metallic and insulating layers and ii) the movement of the shutter flaps is partially controlled by an electric field between the shutter flap and the substrate. The whole mission would be compromised if radiation exposure were to prevent the shutters from opening and closing properly.

This report presents the results of radiation testing of the MSA at 60 K. The temperature was higher than the targeted temperature because of a faulty electrical connection on the test board that produced Ohmic heating. The increased temperature is not expected to affect the results. Our goal was to determine both appropriate bias conditions during irradiation and suitable test procedures to evaluate the MSA's functionality following a TID of 200 krad(Si). (Because of electrostatic charging effects electrons and protons can potentially induce considerably more degradation than gamma rays. Here, we look at the effects of ionization.)

## II. DEVICE DESCRIPTION

### A. Review Stage

The MSA is a MEMS device manufactured from a Si wafer using typical Si processing. The device consists of an array of $365 \times 171$ flaps, each flap having dimension of 100 $\mu$m by 200
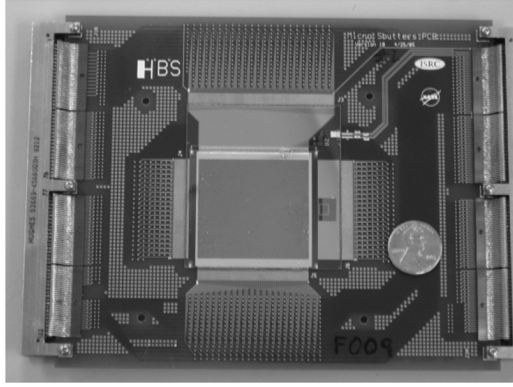
Fig. 1. Microshutter Array mounted on test board. The magnetic field is supplied by a permanent magnet that moves laterally in front of the shutter.
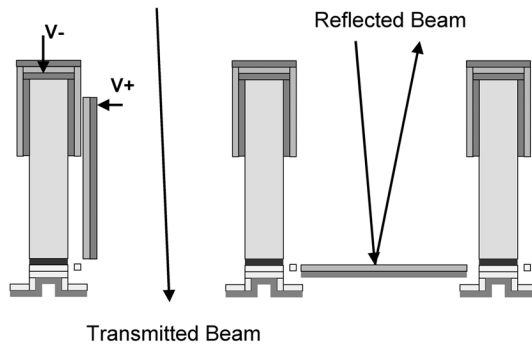


Fig. 2. Two adjacent shutters; the one on the left is open to allow the light to pass through and the one on the right is closed to block the light.

$\mu$m. The flaps are constructed of two insulating and two metallic layers, one of which is also magnetic. Each flap rotates about a hinge along one of its sides: the remaining three sides are separated from the substrate during processing. Fig. 1 is a picture of the shutter array mounted on a test board with all the connections required for controlling the shutters. No electronic control circuitry was on the board during these tests.

Fig. 2 is a diagram showing two adjacent flaps, one open and the other closed. The vertical structure is part of the silicon substrate. In the open position, the flap has pivoted until it comes into contact with the "vertical" support grid that is part of the silicon substrate.

All the shutters are forced open in a two-step process. A voltage differential is first established between the shutters and the substrate by applying positive voltage to the flaps and negative voltage to the substrate through two orthogonal addressing chips (X and Y). However, the voltage differential is, by itself, not sufficient to overcome the restoring force of the hinge. By adding a magnetic force from a permanent magnet, the shutters can be forced open. The magnet is mounted on a track with one rail on either side of the MSA. The magnet moves from one side of the MSA to the other while attached to the track and is driven by a small motor. Once the permanent magnet passes beyond the edge of the MSA where it no longer has any influence on the shutters, the shutters will remain open if the voltage differential is sufficiently large. The final configuration of open and closed shutters is established by reducing the voltage differential to 0 V on all the shutters programmed to be closed.
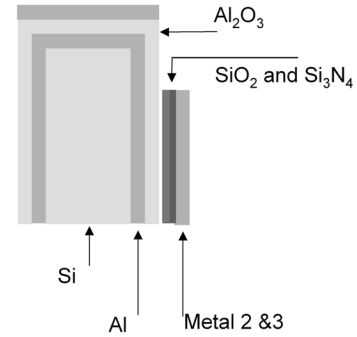


Fig. 3. Diagram showing the details of the layers of metal and insulator for the case where the shutter flap is open and comes into "contact" with the vertical post. Notice the presence of a gap separating the $Al_2O_3$ on the post from the $Si_3N_4$ on the flap. The gap is caused by surface roughness and imperfect alignment of the flap with the post.

Fig. 3 is a diagram showing the metal and insulating layers on the post and the flap. The figure shows that the post (Si) is covered by a metal (Al) and an insulating layer ($Al_2O_3$), whereas the flap consists of two metallic layers (one layer is magnetic) covered by $SiO_2$ and $Si_3N_4$. In the open position, the structure forms a capacitor with the three insulating layers sandwiched between the metal layers. With $V+$ on the flap and $V-$ on the substrate, the electric field across the insulating layers is a maximum, and the shutters would be expected to be most sensitive to the effects of TID.

It should be pointed out that, in the open position, the actual contact area between the shutter and the post is a small fraction of the total shutter area because of surface roughness and imperfect alignment. A small contact area means that over most of the flap's area there is a small gap between the post and the flap that hinders charge generated on one side of the gap from moving to the other side. The result is a reduction in charge separation that, we will argue, is beneficial from a radiation point of view because it results in a reduced TID effect.

## III. TEST SETUP AND DESCRIPTION

The device was mounted inside a dewar under vacuum and cooled to approximately 60 K with liquid nitrogen and liquid helium. The temperature was measured with a Lakeshore DT-470 temperature diode, having an accuracy of 10 mK. No measurements were made of the uniformity of the temperature across the device. The dewar was positioned close to a $Co^{60}$ source where the dose rate, as measured with a Model 35040 Therapy Dosimeter, was approximately 6 krad(Si)/hour. Measurements were made after total doses of 10, 20, 50, 100, 150 and 200 krad(Si).

A light source inside the dewar illuminated the back of the shutter array and, by monitoring the transmitted light, it was easy to see which shutters were open and which were closed. To avoid the tedious task of having to manually count the number of open and closed shutters, a camera was used to gather digital images of the MSA. The camera was positioned outside the dewar and faced the MSA through a glass window in a dewar port. Digital images of the shutter array were taken for every test condition, and after completion of the test, software was used to
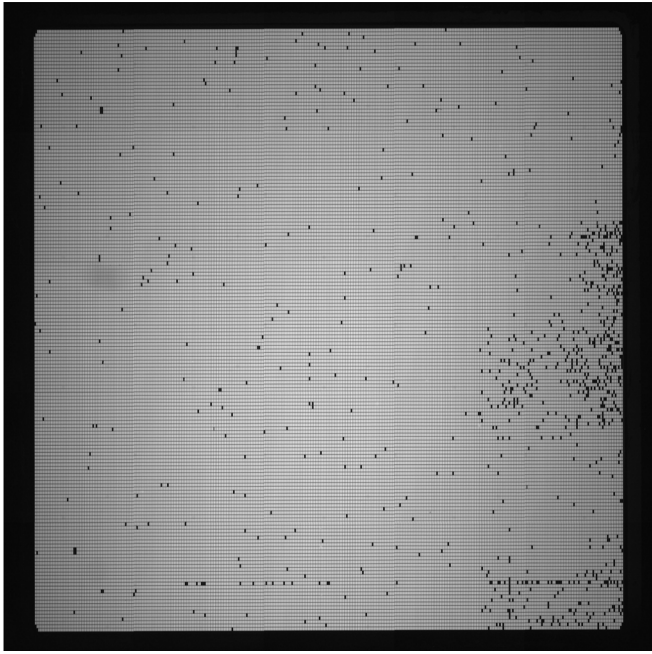
Fig. 4. Digital image of the SMA prior to radiation exposure. All the shutters were commanded to be open. The shutters that failed to open are seen as dark rectangles in the image.

scan the images and record the number of open and closed shutters. There were no partially open shutters. Prior to exposing the MSA to radiation, the number of shutters that were actually operating properly was determined by opening and closing them. A few shutters throughout the array were stuck, some open and some closed.

Prior to each incremental radiation exposure, all the shutters were opened. During irradiation, they were kept open by the application of $+23$ V to the shutter and $-23$ V to the substrate. This configuration was chosen because it produced a maximum electric field across the insulating layers that would be most efficient at separating the radiation-induced charge and, thereby, producing the maximum TID degradation.

Two separate procedures were used for functional testing. In one, the voltages applied to the flaps and shutters were decreased in tandem in relatively large steps, i.e., $+23$ V/$-23$ V, $+20$ V/$-20$ V, $+15$ V/$-15$ V, and $+10$ V/$-10$ V, and the number of open and closed shutters recorded. In the other, the voltage on the substrate (post) was set to 0 V and the voltage on the flaps was gradually decreased in steps of 1 V from 20 V to 10 V. The absence of bias on the substrate reduces the total electric field across the substrate, making it more likely that shutters close when commanded to open, thereby accentuating the number of failed shutters.

## IV. RESULTS

Fig. 4 shows an image of the MSA taken prior to any radiation exposure. All the shutters were programmed open, which allowed the light from the source behind the MSA to reach the digital camera. The image reveals the presence of dark rectangles due to the failure of some shutters to open. The closed shutters are randomly distributed throughout most of the array, with a
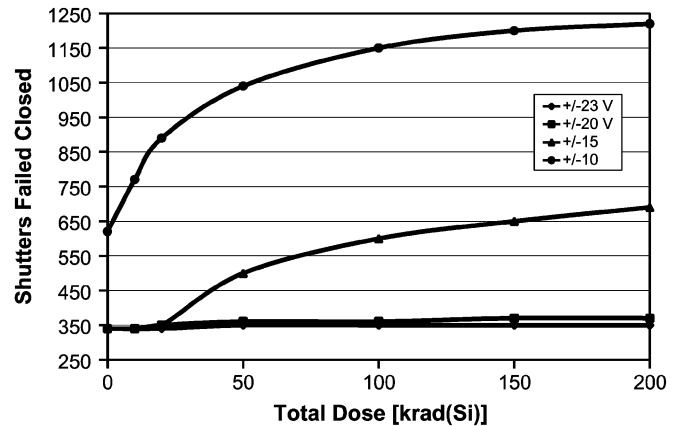


Fig. 5. Number of shutters stuck closed as a function of total dose for four holding voltages.
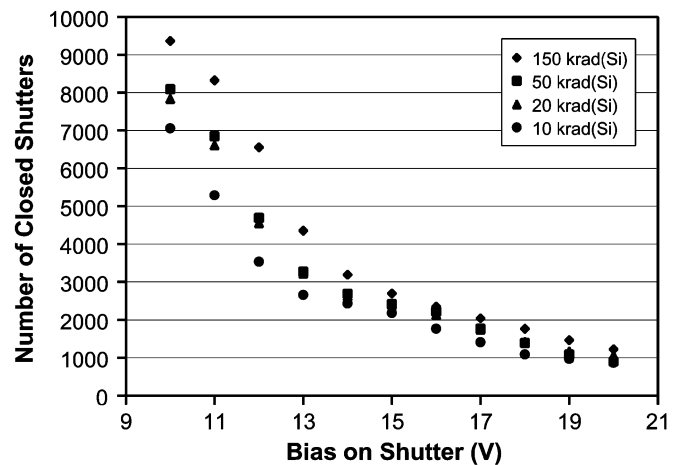


Fig. 6. Number of shutters stuck closed as a function of voltage on shutters. Voltage on substrate (post) was 0 V. (The measurements for 0 Krad(Si) and for 200 krad(Si) were not done).

greater concentration on the right side. The number of non-functional shutters $(\sim 300)$ is a small fraction of the total number of shutters $(\sim 62\,000)$ in the array. It is anticipated that the yield of working shutters will increase as the fabrication process is improved.

Fig. 5 is a graph showing the number of closed shutters as a function of TID for four different sets of holding voltages. The figure shows that for high holding voltages ($+/-20$ V and $+/-23$ V) there are about 350 shutters that were closed when they should have been open, and the number barely changes with dose. However, at lower holding voltages the number increases quite significantly. In particular, for $+/-10$ V, the number of closed shutters increased from 621 prior to irradiation to 1220 after a dose of 200 krad(Si).

Fig. 6 shows the results for the case where the voltage applied to the shutters was reduced from 20 V to 10 V in steps of 1 V. Since the bias on the substrate was 0 V, the total voltage differential was smaller and one would expect more shutters to remain closed when commanded to open, especially as the TID increased. As the threshold for keeping the shutters open was just below 10 V, the minimum holding voltage was set at 10 V. The data show a pronounced dependence of the number of closed
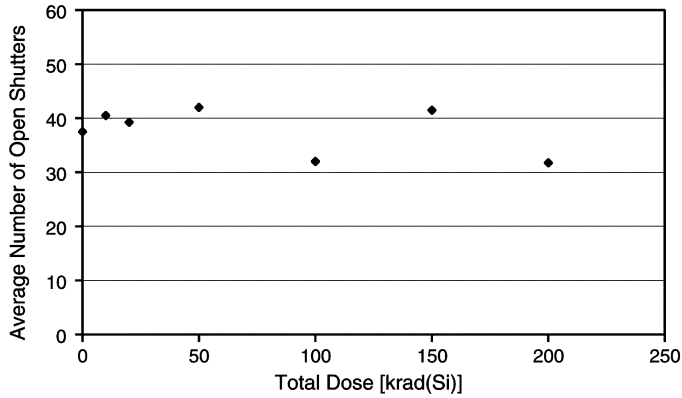
Fig. 7. Number of shutters stuck open as a function of total dose for a series of measurements. Voltage on substrate (post) and shutter was 0 V. The error bars show the standard deviation.
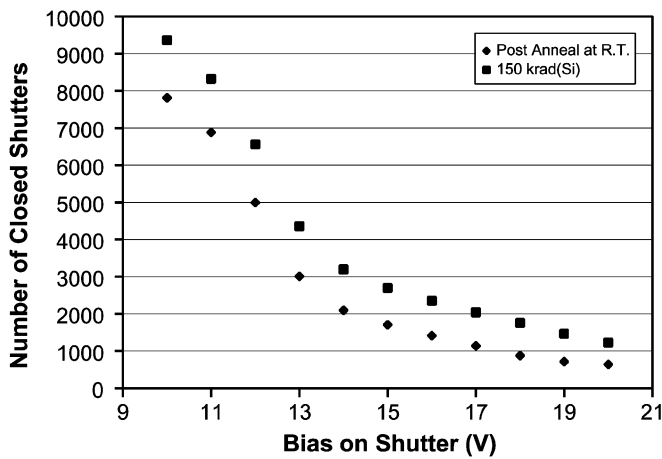


Fig. 8. Number of closed shutters as a function of bias on the shutter after a total dose of 150 krad(Si) and following a room temperature anneal for one month.

shutters on total dose, particularly for low holding voltages. At 10 V the number of closed shutters is about 7000 prior to any radiation dose, and the number increases to approximately 10 000 (roughly 15% of the total number of shutters) after a dose of 200 krad(Si).

Fig. 7 shows the average number of shutters that remained open after all electrical bias was removed. This measurement was repeated numerous times during testing. The data show that the number of shutters stuck open is a small fraction of the total number of shutters in the array, and the number does not change with dose.

The effects of annealing were also studied. After the final dose of 200 krad(Si), the part was brought back to room temperature and allowed to anneal without any applied bias. After a month, the part was again cooled to 60 K and the number of shutters that remained closed when they should have been open was counted as a function of applied bias on the shutter. Fig. 8 compares the data for 150 krad(Si) with that obtained after annealing at room temperature for a month. The figure shows that there is a significant decrease in the number of shutters that are closed when they should be open.

## V. DISCUSSION

The operation of the MSA is affected by ionizing radiation and the effect increases with dose. This is not unexpected, as there are reports in the literature describing how other MEMS, with similar structures, are also affected by ionizing radiation [1]–[6]. Common to all these radiation-sensitive MEMS is the presence of insulators across which electric fields are applied to control or measure movement. In the case of the MSA, an electrical potential difference is applied across three insulating layers sandwiched between two metal layers. The function of the electric field is to assist in opening the shutter flaps and keeping them open once the magnetic field has been removed. Accumulation of radiation-induced charge partially cancels the applied electric field and requires that, for low applied biases, the potential difference be increased to keep the shutters open. The results are of interest because the measurements were done at low temperature on a unique structure, never before tested.

A challenging requirement for the MSA is that, as previously mentioned, it will have to operate at temperatures near 30 K. To date, there are no published reports on the response of MEMS devices to total ionizing dose at very low temperatures. In attempting to analyze the radiation effects in the MSA, one is confronted with a fairly complicated structure, consisting of three different insulating layers sandwiched between metal layers and with relatively few contact points between the $Al_2O_3$ and the $SiO_2$.

In a radiation environment, electron-hole pairs are generated in all three insulating layers. The charge density immediately after irradiation depends on the energy required to produce an electron-hole pair, which is different for each insulating layer. Not only does the MSA's response to radiation depend on the spatial distribution of the deposited charge, it also depends on the magnitude of any applied electric field and on potential barriers between conduction (valence) bands in the insulators that block electrons (holes) from moving from one insulator to another. The generation, movement and trapping of electrons and holes in all three insulators have previously been studied, but, because the MSA was manufactured using different processes and was irradiated at lower temperature, it is uncertain how much of that information is germane to the MSA. In spite of this, we propose a reasonable explanation for how the MSA responds to TID.

The flap contains two insulating layers, $SiO_2$ and $Si_3N_4$, both of which play a role in determining the TID response of the MSA. A brief description of what is known about charge generation and movement in these layers is therefore appropriate.

Previous experiments on metal-insulator-semiconductor structures, incorporating $SiO_2$ as the insulator, indicate that, at 80 K, electrons liberated by ionizing radiation are mobile [7]. There is very little electron trapping, and with a positive bias on the metal, most of the electrons move rapidly to the metal and exit the $SiO_2$. Holes, on the other hand, that would normally move in the opposite direction through the $SiO_2$ via a "thermal hopping" process, are effectively immobile at low temperatures and remain where they were generated. The result is a uniform distribution of positive charge (holes) throughout the $SiO_2$. No

significant changes in hole distribution or electron mobility are expected at 30 K.

The $Si_3N_4$ layer is between the $SiO_2$ and metal contacts on the flap. Two properties of $Si_3N_4$ are relevant to its performance in a radiation environment. The first is that $Si_3N_4$ contains both electron and hole traps, so that many of the electrons and holes generated in the $Si_3N_4$ by ionizing radiation are trapped close to where they are generated [8]. From a radiation point of view, this is beneficial because the trapped electrons and holes cancel each other and minimize the effects of radiation on the operation of the device. The second is the presence of potential barriers between the $Si_3N_4$ and the $SiO_2$ that effectively block the movement of electrons and holes from $Si_3N_4$ into $SiO_2$, but not the reverse [9]. Therefore, a positive bias applied to the shutter flap causes the electrons generated in the $SiO_2$ to move towards the oxide/nitride interface, where most of the electrons will be trapped [10]. Holes in the $Si_3N_4$ are immobile at low temperature. The net result is an accumulation of positive charge in the $SiO_2$.

The third insulating layer that must be considered is $Al_2O_3$, which is part of the post structure. $Al_2O_3$ contains both hole and electron traps [11]. However, the situation is complicated by the fact that the balance between the electron and hole traps is determined by a number of factors, including growth conditions, applied electric field and temperature. Therefore, depending on the aforementioned conditions, the radiation response of the $Al_2O_3$ films could be dominated by electron traps, by hole traps, or the two could largely cancel each other. Without additional experiments, it is not possible to know which one of these situations is the controlling factor. If one assumes the worst case, that the electrons are mobile and the holes are not, the applied bias will force the electrons generated in the $Al_2O_3$ towards the interface with the vacuum, where most of the electrons will be prevented from further movement. By limiting the charge separation, the gap acts to partially mitigate TID effects.

The number of shutters that remain open after the removal of all biases is initially very small $(\sim 40)$, and remains essentially unchanged with increasing dose. The fact that the number of shutters stuck open does not change with dose suggests that the restoring forces provided by the shutter hinges overwhelm the electrostatic forces associated with radiation-induced charge trapped in the insulators. Those shutters stuck in the open position most likely have damaged hinges that lack a restoring force and are the result of a less-than-mature manufacturing process.

As already pointed out, the process used to manufacture the MSA was not yet mature, as evidenced by the yield of properly working devices being less than 100%. Furthermore, variations in the processing caused some of the devices to open while others remained closed when the potential difference was close to the "holding" voltage. It is expected that, as the manufacturing process matures, the number of shutters that fail to operate properly should also decrease, and the distribution of failed shutters at various dose levels should tighten up.

Finally, allowing the MSA to remain at room temperature without any external bias gives rise to a reduction in the number of shutters failed closed. Electric-field induced thermally stimulated annealing of the radiation generated charge is a likely contributor, where the residual electric fields across the insulators arise from the separation of electrons and holes during irradiation.

## VI. Conclusion

Radiation exposure causes an increase in the flaps' holding voltage. The increase is attributed to a buildup of charge in the insulating layers on the flaps and on the substrate post. The buildup of charge partially cancels the applied electric field, which becomes less effective at holding the shutter flaps open. The presence of small gaps between the flaps and posts limits charge separation and, therefore, partially mitigates the TID damage. At high voltages, the number of closed shutters that should be open is small and does not change much with dose. However, at low voltages, close to threshold, the number of closed shutters increases significantly with dose. Therefore, for NIRSPEC on the James Webb Space Telescope, voltage differences close to 40 V will be used to minimize the effects of radiation on the operation of the shutter flaps.

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